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Model-Based Sensor Location Selection for Helicopter Gearbox Monitoring

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MODEL-BASED SENSOR LOCATION SELECTION FOR HELICOPTER GEARBOX MONITORING

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ABSTRACT

A new methodology is introduced to quantify the significance of accelerometer locations for fault diagnosis of helicopter gearboxes. The basis for this methodology is an influence model which represents the effect of various component faults on accelerometer readings. Based on this model, a set of selection indices are defined to characterize the diagnosability of each component, the coverage of each accelerometer, and the relative redundancy between the accelerometers. The effectiveness of these indices is evaluated experimentally by measurement-fault data obtained from an OH-58A main rotor gearbox. These data are used to obtain a ranking of individual accelerometers according to their significance in diagnosis. Comparison between the experimentally obtained rankings and those obtained from the selection indices indicates that the proposed methodology offers a systematic means for accelerometer location selection.

1 INTRODUCTION

Present helicopter gearboxes are significant contributors to both flight safety incidents and maintenance costs. For example, for large/medium civil transport helicopters in the period 1956-86, gearboxes were the principal cause of 22% of the accidents which often resulted in loss of life and the aircraft [1]. Rapid and reliable fault diagnosis of helicopter gearboxes is therefore necessary to prevent major breakdowns due to progression of undetected faults, and to enhance personnel safety by preventing catastrophic failures.

Fault diagnosis of helicopter gearboxes, like most rotating machinery, is based upon vibration monitoring. Therefore, an important issue in helicopter gearbox diagnostics is determination of the number of accelerometers to be used for monitoring and their location on the gearbox housing. Accelerometers are generally located by experts based on their proximity to gearbox components, orientation, and ease of mounting on the housing. However, the fundamental problem with this approach is that experts often demand too many sensors to be monitored on-line by the on-board computer. Another motivation for reduction of the number of accelerometers is the cost associated with the extra mountings, cabling, signal conditioning equipment, etc. As such, experts are often faced with the dilemma as which sensor(s) to eliminate without seriously undermining diagnosability of the gearbox. This calls for a methodology for quantifying the significance of various accelerometer locations in diagnosis.

Ideally, the significance of each accelerometer could be determined empirically by comparing diagnostic results with and without the accelerometer. This, however, would require a comprehensive set of measurement data associated with all component faults in the gearbox, which is generally not available. As a compromise to empirical assessment of accelerometer values, a model-based methodology for accelerometer location selection is proposed in this paper that is independent of measurement-fault data. The basis for this methodology is an influence model between component faults and accelerometer readings obtained from a lumped mass model of the gearbox. The proposed sensor selection methodology uses the following criteria to evaluate the significance of individual locations: (1) the diagnosability of the system; i.e., the ability to diagnose faults in each component, (2) accelerometer coverage; i.e., the number of components an accelerometer can monitor, and (3) the level of redundancy between accelerometers in their coverage of various components. The above three criteria are quantified by three indices: diagnosability, coverage, and redundancy, which are computed using the influence model of the gearbox. Individual or groups of accelerometers are then ranked according to their impact on the value of these indices when accelerometers are discarded. The accelerometers whose exclusion provides the greatest loss in the value of indices are assigned the highest rank to indicate their significance in diagnosis.

The validity of the proposed sensor location selection indices is evaluated experimentally. For this, measurement-fault data obtained from an OH-58A main rotor transmission are used to rank the accelerometers for their effect on diagnosability of components. A comparison between these experimentally obtained rankings and those from the selection indices indicate that the indices offer a viable means of evaluating the significance of accelerometers.

2 INFLUENCE MODEL

The proposed methodology requires an influence model to represent the effect of various component faults on accelerometer readings. Ideally, these influences should be defined so as to represent the strength of vibration caused by a component fault monitored by each accelerometer. However, the strength of vibration depends on the attenuation property of the transfer path between the component and the accelerometer, which, in turn, is a function of parameters such as the moment of inertia, stiffness, and damping of the components in the path [2,3]. As such, computation of the vibration transfer would require consideration of all the vibration travel paths associated with each component-accelerometer pair and knowledge of the parameters associated with each path [4]. Such a detailed knowledge of the gearbox is practically infeasible [5]. For example,

the gear mesh stiffness is obtained by considering the gear tooth as a non-uniform cantilever beam [6,7], as a function of the cross-section of the tooth at the point of loading as well as load variation due to changes in direction of load application [6,4,8], friction between the meshing teeth [9], contact ratio [10], the type of gears (spur, helical, etc.) [6,7,8], and gear errors such as profile, transmission and manufacturing errors [3,8]. Similarly, the stiffness of bearings is a time-varying, non-linear function of bearing displacement and the number of rolling elements in the load zone, as well as the bearing type (roller, ball, etc.), axial preload, clearance, and race waviness [11,12,13].

In view of the difficulties associated with computing the strength of vibration, as an alternative, an approximate influence model is obtained to represent the average strength of vibration across all frequencies [5]. To compute this average vibration, several simplifications are considered: (1) a lumped mass model of the gearbox is considered; (2) in the absence of accurate values for stiffness coefficients, only the average static values for the stiffness coefficients are used [6,11,14]; (3) damping ratios of bearings and shafts are neglected [6]; (4) the damping ratio of gears, estimated between 0.03 and 0.17 [15], is set at 0.1 for all gears; (5) the cross-coupling terms in the stiffness matrix are neglected; (6) only the shortest vibration travel path between component-accelerometer pairs is considered; and (7) vibration transfer through the housing is neglected. Using the above simplifications, the vibration caused by a faulty component can be simulated by considering an excitation source at the component, which consists of unit amplitude sine waves of all frequencies within the bandwidth. In this research, the average vibration transferred from each component to an accelerometer is characterized by the root mean square (RMS) value of vibration across all frequencies [5].

The simplifications used to facilitate estimation of the RMS values result in only approximate RMS values. Such approximate RMS values would, in turn, result in approximate influence values which may seriously affect the accuracy of diagnosis. In order to cope with the approximate nature of influences, fuzzy variables [16] are used where the influences are not treated as values but as variables with a range. The influence values are, therefore, transformed into the fuzzy variables: nil: (0, 0.1), low: (0.1, 0.4), medium: (0.4, 0.6), high: (0.6, 0.9) and definite: (0.9, 1), so as to define the fuzzy influences in the influence model [5].

3 SELECTION INDICES

In the proposed sensor selection methodology, three indices are considered to represent the effectiveness of accelerometers in monitoring various gearbox components. These indices, which are computed based on the influence model, are the diagnosability index, coverage index, and redundancy index. As discussed earlier, influences represent the average vibration registered by accelerometers due to component faults. Therefore, they can be used to characterize the effectiveness of each accelerometer by measuring the number of components it covers, the amount of energy it receives from these components, and its relative redundancy with respect to other accelerometers.

The diagnosability index represents the amount of influence each component has on all the accelerometers. As such, the diagnosability index is defined as the sum of the influences for that component, as

$$D_i = \sum_j \frac{u_{ij} + l_{ij}}{2} \tag{1}$$

where u_{ij} and l_{ij} represent the upper and lower limits of the fuzzy influence between component i and accelerometer j, and the summation is carried out over all accelerometers j. One possible utility of the diagnosability index is that it ensures a minimum level of diagnosability for each component given the combination of accelerometers selected.

The coverage index is the measure of reach of each accelerometer. It represents the total influence between an accelerometer and all the components within the system. The coverage index for each accelerometer is defined as:

$$C_j = \sum_i \frac{u_{ij} + l_{ij}}{2} \tag{2}$$

where u_{ij} and l_{ij} represent the upper and lower limits of the fuzzy influences between the accelerometer j and gearbox component i, and the summation is carried over all components i. One possible use of the coverage index is to ensure that each accelerometer has a minimum level of coverage.

The redundancy index measures the effectiveness of accelerometers by measuring their overlap with other accelerometers. In terms of fuzzy influences, an accelerometer is redundant if the components it covers are already covered with higher influence values by other accelerometers. The redundancy index is measured for each accelerometer as:

$$R_j = \sum_i [I_{ij} - MAX(I_{il}, \text{ for every } l \neq j)] \tag{3}$$

where $I_{ij} = (u_{ij} + l_{ij})/2$ represents the average value of each influence, and the summation is carried over all components i. As defined, a larger value of R_j indicates a smaller overlap between accelerometer j and others.

4 EXPERIMENTAL

The effectiveness of the sensor selection indices was evaluated using experimental measurement-fault data from an OH-58A main rotor gearbox. The configuration of this gearbox is shown in Fig. 1, and the location and orientation of the eight accelerometers used for vibration measurement are shown in Fig. 2. Vibration data were collected at the NASA Lewis Research Center as part of a joint NASA/Navy/Army Advanced Lubricants Program [17]. The vibration signals were recorded from eight piezoelectric accelerometers (frequency range of up to 10 KHz) using an FM tape recorder. Two magnetic chip detectors were also used to detect the debris caused by component failures. Accelerated fatigue tests were performed where the gearbox was run under a constant load and was disassembled and inspected periodically, or when one of the chip detectors indicated a failure. A total of five tests were performed, where each test was run between nine and fifteen days ranging from four to eight hours a day. A total of eleven failures occurred during these tests. They consisted of three cases of planet bearing pitting fatigue, three cases of sun gear pitting fatigue, two cases of top housing cover cracking, and one case each of spiral bevel pinion pitting fatigue, mast bearing micropitting, and planet gear pitting fatigue. In order to identify the effect of faults on the vibration data, the vibration signals obtained from the five tests were digitized and processed by a commercially available diagnostic analyzer. For analysis purposes, only one data record per day was used to represent gearbox vibration for each test [18].

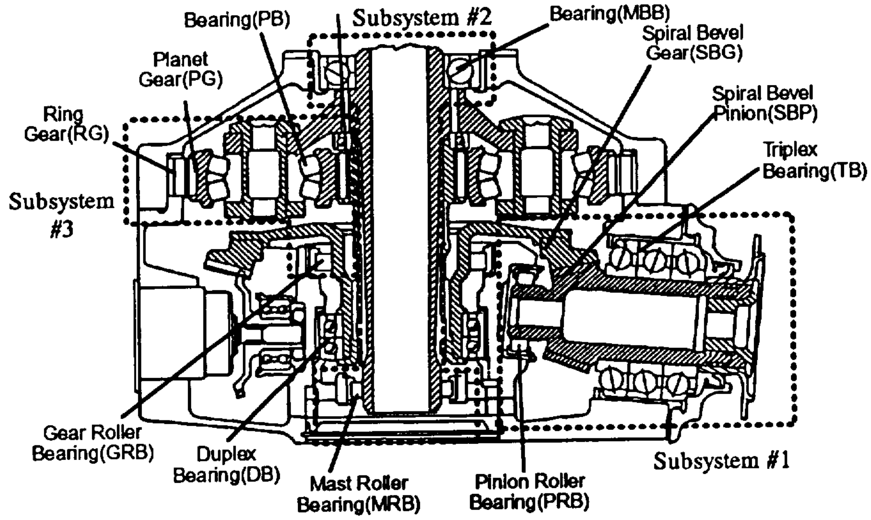

Figure 1: Configuration of the OH-58A main rotor gearbox, with the components classified into subsystems for diagnosis.

5 EVALUATION

The first step in the evaluation process was determination of the influence model. For the OH-58A gearbox five primary vibration travel paths were identified: (1) Duplex Bearing-Spiral Bevel mesh-Triplex Bearing, (2) Duplex Bearing-Sun-Planet mesh-Ring Gear (3) Mast Roller Bearing-Main Shaft-Mast Ball Bearing (4) Ring Gear-Planet Bearing-Mast Ball Bearing, and (5) Duplex Bearing-Sun Planet mesh-Mast Ball Bearing. The first travel path was in connection to accelerometers 4, 5, and 6, where as all the other paths were connected to accelerometers 1, 2, 3, 6, 7, and 8. The RMS values of vibration were then computed using the lumped mass model of these paths, and used as the basis for defining the fuzzy influence model. It should be noted that due to fuzzification of influences, components which are adjacent to each other are likely to have the same fuzzy influences and hence, become indistinguishable for ranking purposes. To cope with this problem, the OH-58A gearbox was divided into three subsystems (see Fig. 1): Subsystem 1 (the input subsystem), Subsystem 2 (the output subsystem), and Subsystem 3 (the planetary subsystem), and the influences between the subsystems and accelerometers were obtained by averaging the influences of components within each subsystem (Table 1).

Using the influence model in Table 1, the three sensor selection indices were computed for the complete suite of 8 accelerometers. Next, in order to evaluate the effect of individual accelerometers on the value of these indices, the row associated with each accelerometer in Table 1 was removed and the three indices were recomputed for the resulting suites of 7 accelerometers. The estimated loss, $\hat{L}_s$, in the quality of diagnosis with various suites of 7 accelerometers was defined as:

$$\hat{L}_s = \sum_{i=1}^{3}(D_{i8} - D_{is}) + \sum_{j=1}^{8}(C_{j8} - C_{js}) + \sum_{j=1}^{8}(R_{j8} - R_{js}) \tag{4}$$

where D_{is} denotes the diagnosability index of Subsystem i with suite s, C_{js} represents the coverage index of accelerometer j with suite s, and R_{js} denotes the redundancy index of accelerometer j

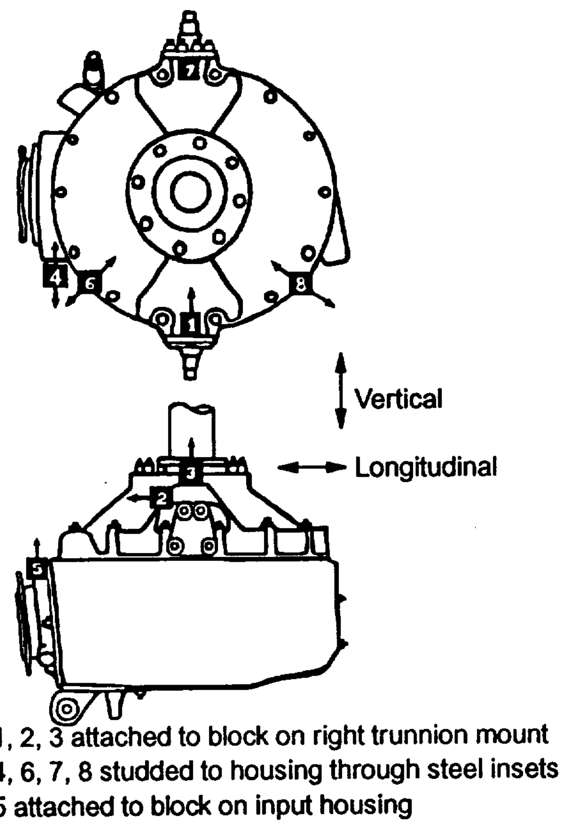

Figure 2: Location of the accelerometers on the test stand.

with suite s. This loss value was then used to classify accelerometers into one of four categories, to signify their value in diagnosis. The accelerometer whose exclusion resulted in the highest loss was classified into the first category, while the accelerometer with the least loss was placed in category 4. The above strategy was also used to classify groups of accelerometers, by computing the loss values associated with suites of 6, 5, 4, 3, 2, and 1 accelerometer(s).

Experimental evaluation of the rankings from the three indices was obtained via a model-based diagnostic system [5]. The overview of this model-based diagnostic system is presented in Fig. 3. The inputs to this system are the vibration features obtained by processing the raw vibration signal from the OH-58A accelerometers. These vibration features are first input into an unsupervised fault detection network to identify the presence of faults in the gearbox. Once the presence of a fault is prompted by the fault detection network, fault diagnosis is performed by the Structure-Based Connectionist Network (SBCN) whose weights comprise the fuzzy influences. The inputs to SBCN are abnormal features, which are separately identified by an unsupervised pattern classifier, referred to as the Single Category-Based Classifier (SCBC) [19]. The SCBC is designed to identify the degree of abnormality in individual features by comparing them against their normal-mode values. To perform diagnosis, these abnormality-scaled features are propagated through the weights of SBCN to yield as outputs fault possibility values p_i between 0 and 1 for individual gearbox subsystems.

The SBCN was used to quantify the significance of individual accelerometer locations in di-

Accelerometer	Subsystems		
	Input	Output	Transmission
1	-	M	H
2	-	M	H
3	-	M	H
4	H	-	L
5	H	-	M
6	M	M	H
7	-	M	H
8	-	M	H

Table 1: Influences of the three subsystem on the eight accelerometers. The influences shown are: '-' Nil, M Medium, H High.

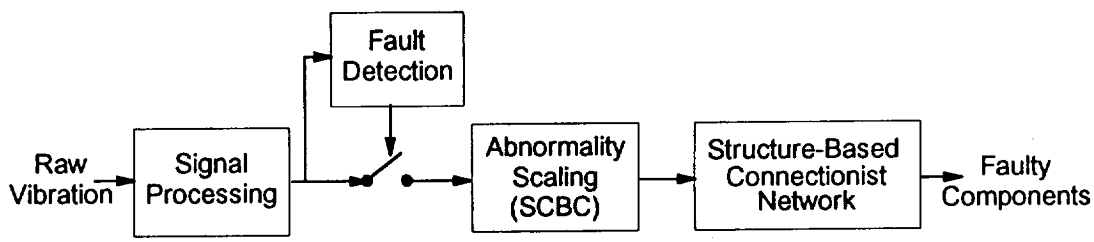

Figure 3: Overview of fault detection and diagnosis in the proposed model-based diagnostic system for helicopter gearboxes.

agnosis of the OH-58A gearbox. For quantification purposes, a performance index P was defined to represent the accuracy of the diagnostic results obtained from SBCN. This performance index had the form

$$P_i = \sum_{faults} p_i \tag{5}$$

where p_i represents the fault possibility value of the ith subsystem and the summation was carried out over all the available faults that had occurred during the OH-58A experiments. In SBCN, to study the significance of each accelerometer on the diagnostic results, P was recomputed for various accelerometer suites. The experimental loss function, L_s, was then defined to represent the differential in the P value for each of the suites relative to its value for the complete set of 8 accelerometers as:

$$L_s = \sum_{i=1}^{3} \left[\frac{P_{i8} - P_{is}}{P_{i8}} \right]^2 \tag{6}$$

where P_{is} represents the performance index of the ith subsystem obtained for suite s, and P_{i8} denotes the performance index of this Subsystem with the complete suite of 8 accelerometers. The summation is carried over the 3 subsystems to obtain the total loss. The L_s obtained for suites of the same size were then normalized to have values between 0 and 1 and used for ranking purposes. As with the selection indices, the excluded accelerometer that caused the greatest loss

was assigned to the first category. The normalized loss values and the associated ranks for suites of 7 accelerometers are included in Table 2 along with the estimated loss and ranks obtained from the selection indices. In this table, accelerometer locations with the highest loss are assigned a rank of 1 to indicate that they are the most important ones for diagnosis. The rankings indicate that accelerometer 5, the elimination of which resulted in the highest loss, is the most important for diagnosis. The results for these suites indicate that for accelerometers 1, 2, 4, 5, and 8 the estimated and diagnostic ranks match, and that there is a mismatch by 1 rank for accelerometer 3, 6, and 7. A summary of matches and mismatches for suites consisting of a smaller number of accelerometers is given in Table 3. The results indicate that out of 254 possible suites, 150 suites have an exact match in estimated and diagnostic ranks, 103 mismatch by 1 rank and 1 suite mismatches by 2 ranks.

Accelerometer Excluded	Indices		Diagnostic	
	Loss	Rank	Loss	Rank
1	0.425	3	0.347	3
2	0.353	3	0.464	3
3	0.353	3*	0.100	4
4	0.100	4	0.149	4
5	1.000	1	1.000	1
6	0.518	3*	0.126	4
7	0.425	3*	0.223	4
8	0.425	3	0.371	3

Table 2: Ranks obtained from the selection indices and diagnostic ranks for suites of 7 and 6 accelerometers. A '*' indicates a mismatch between indice-ranks and diagnostic ranks.

Suites of	Match Exactly	Mismatch by		
		1	2	3
7	5	3	0	0
6	16	12	0	0
5	35	21	0	0
4	40	29	1	0
3	32	24	0	0
2	17	11	0	0
1	5	3	0	0
Total	150	103	1	0

Table 3: Summary of comparison of ranks obtained from the three sensor selection indices and diagnostic ranks for suites of 7, 6, 5, 4, 3, 2, and 1 accelerometers.

The results summarized in Table 3 indicate that the selection indices are effective in assessing

the value of individual (suites of) accelerometers. Using the influence model as the common point between the selection indices and SBCN de-emphasizes the effect of modeling errors. The influence model alone, however, does not ensure a perfect match between the two rankings because the diagnostic rankings from SBCN also depend on the experimental data as well as the performance of SBCN's other components (detection network and SCBC). The experimental data, although one of the most complete sets available in the industry, are still not as comprehensive as required for a complete evaluation of the method. The main limitation is the absence of faults that could signify the value of some accelerometers which otherwise may have been assigned a lower rank. For example, there is only a single fault in Subsystem 2 (mast bearing micropitting), therefore, accelerometers that are important in isolating other faults within this Subsystem may appear as unnecessary. Although the rankings obtained from the selection indices agree well with those obtained from the diagnostic results, they can be improved further to enhance their effectiveness. One possibility is the redundancy index which may be refined further so as to include spatial redundancy of accelerometer locations as well.

6 CONCLUSION

A methodology is introduced for evaluating the significance of accelerometer locations in diagnosis of faulty gearbox components. This methodology, which is based on the influences between components and accelerometers, uses three indices for evaluation of accelerometers. The diagnosability index represents the coverage each gearbox component receives from all the accelerometers, the coverage index denotes the reach of individual accelerometers, and the redundancy index characterizes the overlap between the accelerometers. These indices were evaluated together in estimating the diagnostic quality of various accelerometer location suites for an OH-58A gearbox. The results indicate that the rankings provided by the indices agree well with the actual rankings obtained from a diagnostic system.

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